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Structural Relationships Of Selected Tree Species at Several Mid-Latitude Deciduous Forest Sites in Virginia

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14. ABSTRACT: Many computer models currently used by the U.S. Army require input of forest structural attributes. Knowledge of these attributes impacts cross-country mobility, cover and concealment, bivouac, etc. Access to direct ground measurement of these required parameters in denied areas is not always possible. This necessitates the capability to generate accurate estimates of selected forest features. Airborne imagery provides fairly high accuracy for such elements as tree crown diameter and tree height. Tree stem diameter (i.e., diameter at breast height (d.b.h.)) is an important parameter that cannot be measured directly by these sensors. This work involves the development of models to estimate d.b.h. from average crown diameter. More than 650 trees were measured in a series of 25 data collections at 11 sites in northern and north-central Virginia. The sites were dominated by uneven-aged deciduous trees, both forest grown and open grown. Models to predict d.b.h. from average crown diameter were generated and accuracy assessments are provided.

15. SUBJECT TERMS

Tree measurements, crown diameter, tree height, deciduous forest, statistical models, regression analysis, diameter at breast height (d.b.h.)

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

PREFACE

This report was prepared under DA Project 61110252C, Work Unit K0801, "Terrain/Climate Interactions."

This study was conducted during the period March 1998 to June 1999 under the supervision of Kevin Slocum, Team Leader, Terrain Data Generation Branch; William Z. Clark, Jr., Chief, Terrain Data Generation Branch; and Joseph E. Swistak, Chief, Topographic Research Division.

Dr. William E. Roper was Director and Colonel Gary Thomas was Commander and Deputy Director of the U.S. Army Topographic Engineering Center at the time of report publication.

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STRUCTURAL RELATIONSHIPS OF SELECTED TREE SPECIES AT SEVERAL MID-LATITUDE DECIDUOUS FOREST SITES IN VIRGINIA

I. INTRODUCTION

Forest management schemes have historically used a variety of individual stem and whole-stand structural parameters in the design, implementation, and assessment of silvicultural treatments. These variables include:

- age,
- diameter at breast height (d.b.h.),
- height,
- crown diameter,
- crown surface area,
- stem density,
- basal area, and
- canopy cover.

Many more stem and stand metrics are calculated from these, and other, basic forest measurements. By developing relationships between forest measurements and estimated wood volume, either as biomass or in board feet, managers can implement stand improvement treatments. Both simple and complex models have been derived to design reforestation plans, thinning regimes, chemical treatments, and harvest schedules. The application of these models has traditionally been on intensively managed, even-aged, monocultural timber compartments. As with any agricultural system, successful and profitable silviculture requires the elimination (or at least the reduction) of natural variability in the timber crop to increase yield.

This preliminary research effort was conceived as part of a remote sensing project that employed high spatial resolution (i.e., ~ 1 meter), multispectral digital imagery over a small study site at Fort A.P. Hill, VA. The overall program objectives included an evaluation of the utility of the airborne imagery for forest inventory. The application of several forest inventory parameters, such as average stand d.b.h., canopy cover, and average stem height, was not intended to include silviculture but was to provide input into military tactical cross-country mobility (Broughton and Addor, 1968; Bullock, 1988) and cover and concealment models. Assuming that a military tactical action will happen in an area where ground reconnaissance is denied, forest canopy structural and compositional information needs to be extracted from the multispectral imagery. This limits the forest inventory variables to dominant and codominant overstory characteristics such as forest type (i.e., conifer vs. hardwood vs. mixed), stand density (i.e., number of clearly separable crowns per unit area), and individual crown width or area. The goal was to then predict the remaining forest structural components using empirical models derived from statistically valid field data. The preliminary analysis of the ground truth data, collected within fixed-area sample plots, suggested a correlation among tree height and d.b.h. Initially, individual crown diameter estimates were manually measured and extracted from the imagery on stems that were easily located on the ground. The same stems were then located on the ground and measured to evaluate the accuracy of the image-derived crown estimates. This additional preliminary sample, that included measurements of d.b.h. and height, displayed a relationship between crown diameter and d.b.h. A larger sampling scheme was devised and implemented to quantify these forest structural relationships.

The authors were aware that the development of empirical relationships to model complex stand dynamics has been an ongoing process. Particularly in the last 50 years, forest industry researchers have developed mathematically-based methods for producing the highest quantity of wood fiber within the shortest rotation cycles. The majority of the models are applicable to very specific and unique timber compartments comprised of a single species (e.g., loblolly pine), with a unique genotype (e.g., disease resistance or rapid shoot growth), and grow on well-groomed plantations with documented site indices; however, the variables within these growth and yield models include the standard forest inventory variables listed above. The results of these models produce estimates of variables such as crown competition index (CCI), crown competition factor (CCF), stand density index, and tree-area ratio.

This research began in March 1998 when a field data collect team was established to conduct ground-truth measurements of selected trees at Fort A.P. Hill, VA. Several airborne sensors estimated attributes for 62 candidate trees, and field ground-truth was subsequently required to determine sensor and operator estimation accuracy from photo measurements. Ground-truth consisted of measurements of tree height, mean crown diameter, and d.b.h. When the ground-truth measurements were examined, it became readily apparent to the field data collect team that straightforward mathematical relationships existed among these measured tree attributes, especially between crown diameter and d.b.h.

It was decided to increase the size of the tree database for selected species in order to determine if the preliminary relationships seen in the 62 specimens held true for a much larger data set. Also, there was an interest in examining any differences in these relationships that might exist in forest-grown vs. open-grown trees as well as natural vs. planted specimens.

II. BACKGROUND

The correlation between crown diameter and d.b.h., as well as crown diameter to stem height, both total and merchantable height, has been used to estimate timber volumes from large-scale aerial photography. This basic application of photogrammetry to forest inventory is well documented in remote sensing texts, including Lillesand and Keifer (1994) and Avery and Berlin (1992). Ultimately, this is the intended application area for the statistical models presented in this report. One potential problem is the migration of the crown diameter/d.b.h. models presented, i.e., are these models valid in forests outside of the mid-Atlantic region of the United States?

Some examples of previous work in modeling the relationships among forest canopy structural characteristics began in the early 1900's when Duchaufour concluded that the crown diameter of beech (*Fagus*) was linearly related to d.b.h. (Dawkins, 1964). Dawkins describes how, during the first half of the 20th century, other European forest researchers established that crown diameter and d.b.h. maintained a linear relationship for fir (*Abies*), spruce (*Picea*), birch (*Betula*), and Douglas-fir (*Psuedotsuga*). Dawkins also examined the correlation between crown diameter and d.b.h. for 15 commercial tropical tree species including Honduran mahogany (*Swietenia macrophylla*) and balsa (*Ochroma lagopus*). The relationships all are essentially linear. Dawkins put forth that the relationships are strong enough that they can be used by photo interpreters to evaluate forest productivity from imagery, thus saving time, money, and the effort required to physically measure these forest stands, many of them in quite remote locations. Cairns (1950) examined the crown/d.b.h. relationship as it relates to aerial photo volume tables. He notes that crown diameter is a function of tree volume through its relation to d.b.h. since the "... size of the crown is an expression of the assimilative capacity of the tree, and is therefore related to wood production and stem size." Cairns also notes that the crown diameter-d.b.h. relation is fairly constant for a given species in fully stocked even-aged stands.

Sprinz and Burkhart (1987), in a paper that examined the crown diameter and d.b.h. relationships in loblolly stands, used three and four independent variables in linear models. They arrived at high coefficients of determination when predicting d.b.h. ($r^2 > 0.88$) for loblolly pine stands. As a guide to the stocking of sugar maples, Smith and Gibbs (1970) examined 301 specimens at 18 sites in the eastern and central portions of the United States and concluded that there is a "... strong correlation between tree diameter and average crown diameter." Their analysis showed that there were no substantial differences among geographic subregions in the crown diameter/stem diameter relationship. They developed a single linear equation to express this relationship ($r^2 = 0.84$).

Lamson (1987) examined 9 species of trees in unmanaged, even-aged, mixed hardwood stands in West Virginia in terms of crown diameter/d.b.h. relationships. Lamson found that ordinary least-squares linear regressions performed the best in expressing this relationship (range of $r^2 = 0.59$ to 0.68). Minor (1951) investigated the crown diameter/d.b.h. relationship for more than 2,500 loblolly and longleaf pines in 38 plots in Louisiana. He concluded that a linear equation well expresses the relationship between these two variables (range of $r^2 = 0.76$ to 0.79). Krajicek, Brinkman, and Gingrich (1961) measured 340 open-grown trees in eastern Iowa in a study of crown competition. The crown diameter/d.b.h. relationships were linearly related for white oaks, black oaks, hickory, and Norway spruce. Coefficients of determination were high (range of $r^2 = 0.93$ to 0.98). They found that the close relationship for crown diameter and d.b.h. were nearly constant within a species.

III. METHODOLOGY

A series of 25 field data collects were conducted at 11 different locations from March 1998 through March 1999. A total of 663 trees were measured for crown diameter, height, and d.b.h. To these data were added an additional 13 loblolly pines measured during the summer of 1998 at Fort A.P. Hill, VA and 13 loblolly pines measured during another research project at Parramore Island, VA. A total of 689 trees comprise the database. The analysis contained in this report applies to 637 specimens.

1) **Measured Tree Attributes**. The three measured tree attributes were crown diameter, tree height, and d.b.h. Standard measurement techniques were employed (see Avery, 1994).

a. Crown Diameter. Two individuals using a logger's tape or an open-reel fiberglass tape measured this attribute. Two measurements were obtained – one representing the major crown axis and the other the minor crown axis. Crown axis is determined by estimating the actual drip-line of the crown. Precision was on the order of 1 foot. These values were then summed and divided by 2 to obtain an average crown diameter.

b. Tree Height. The field team member positioned himself 100 feet from the candidate tree and, using a clinometer, sighted the base of the tree first, and then sighted the uppermost tip of the crown directly over the trunk (bole). The absolute difference between these two measurements translates into the tree's height. Precision was on the order of 1 foot.

c. Diameter at Breast Height (d.b.h.). The circumference of the tree is measured by placing a diameter tape around the tree approximately 4.5 feet (1.37 m) above the ground. The tape graduations are based on the relationship between diameter and circumference of a circle and provide a direct reading of the d.b.h. to a precision of 0.1 in. It was necessary to use tree calipers in several instances because large vines of poison ivy (*Rhus radicans*) grew around the trunks. When the calipers were employed, two measurements of the trunk were obtained – the major axis and the minor axis. They were then averaged to obtain the d.b.h. A number of trees were measured using both the calipers and the diameter tape to determine the relationship between the two measurement techniques. All the measured values were < 0.25 in. (< 0.64 cm) of each other.

2) **Specimen Selection**. The trees analyzed herein represent both open grown and forest grown specimens. Many are natural, whereas others are planted. Open-grown trees develop full, deep crowns and may possess branches close to the ground. Forest-grown specimens possess crowns that recede vertically and decrease in growth rate horizontally as competition for light increases (Farrar, 1961; Larson, 1963). Some specimens with open-grown characteristics were found within the forest proper. These trees appear to have matured in an open surrounding, but now reside within a forest of much younger companions. Likewise, a number of trees possessing forest-grown characteristics were

found in open surroundings that were created by man's activities or because of the demise of the tree neighbors.

The field data collect teams avoided specimens that could be termed "irregular." These are trees that may have had multiple trunks or that possessed swelling, bumps, depressions, distortions, or small to medium secondary branches at the d.b.h. level. Also eliminated from consideration were trees with highly irregular or broken crowns, those that leaned appreciably from the vertical, and those that exhibited signs of stress and/or disease. In selecting the collection sites, an effort was made to ensure that in the final data set, each species had been sampled throughout the full range of available d.b.h. sizes – from sapling through specimens that could be considered "old-growth."

For the statistical analyses, it was decided only to consider those tree specimens with a d.b.h. < 60.0 in. (152 cm). In typical mid-latitude forests, trees with breast height diameters greater than this value would be considered a rarity. In addition, Tubbs (1977) noted that trees with very large d.b.h.s exhibited much variation in their structure. In the entire database, seven specimens had d.b.h. values > 60.0 in. Of these, six were *L. tulipifera* and one was *Fraxinus americana*, the latter a planted specimen at Mount Vernon, VA with a plaque indicating a planting date of 1785. Overall, the six *L. tulipifera* represent open-grown relics from the distant past. Several of these large relics functioned as property boundaries in the old metes and bounds system of surveying. Rusty pieces of barbed wire were found embedded deep within their trunks. Others served as landscape pieces around long-forgotten homesteads. At locations such as Mount Vernon and Montpelier, a number of these trees had been planted in the latter part of the 1700s. Although these larger relics are not included in the statistical analyses, they do appear on Figure 9. This figure provides the reader with an indication as to where these giants fall in relation to the rest of the deciduous species that were measured. In addition, this graph also contains U.S. National Champion big trees (American Forests, 1998) for each analyzed deciduous species appearing in this report.

3) **Trees Species**. The field data collection sites typically support mixed forests dominated by oaks, yellow-poplar, and sweetgum, along with loblolly and Virginia pine. This has been referred to as a "midlatitude summer-green deciduous forest" (Strahler and Strahler, 1987). Bailey (1995) refers to this region as the "Southeastern Mixed Forest Province." The trees selected for measurement were those that were representative of the most abundant species at each site (Burns and Honkala, 1990a, 1990b; Little, 1984). The primary species and species group includes:

1. White Oak Group – consisted primarily of white oak (*Quercus alba*) with a minor constituency of chestnut oak (*Q. prinus*) and post oak (*Q. stellata*). [142 specimens]

2. Black Oak Group (a.k.a. Red Oak Group) – dominated by black oak (*Q. velutina*) and southern red oak (*Q. falcata*) with minor amounts of willow oak (*Q. phellos*), pin oak (*Q. palustris*), scarlet oak (*Q. coccinea*), and northern red oak (*Q. rubra*). [151 specimens]

3. Yellow-poplar (*Liriodendron tulipifera*) – also known as tulip-poplar or tuliptree. [131 specimens]

4. Sweetgum (*Liquidambar styraciflua*) – also known as redgum, sapgum, and starleaf-gum. [59 specimens]

5. American beech (*Fagus grandifolia*) – a common understory species at many of the data collection sites and also a co-dominant species at several sites. [102 specimens]

6. Loblolly pine (*Pinus taeda*) – also known as oldfield pine, North Carolina pine, and Arkansas pine. This is an introduced species in the data collect areas. Many were planted in park-like settings while others were planted in a plantation-like fashion. [52 specimens]

7. Red maple (*Acer rubrum*) – also known as scarlet maple. Included are 2 specimens of black maple (*Acer nigrum*) and 1 of sugar maple (*Acer saccharum*). The small number of measured individual stems was because many candidate maples were located in marshy, swampy areas generally inaccessible to the data collect teams. This species is not included in the individual species statistical analyses, but is included in the deciduous analyses. [25 specimens]

8. Virginia pine (*Pinus virginiana*) – also known as Jersey pine and spruce pine. Because of insufficient numbers, this species was not statistically analyzed. [14 specimens]

9. Several other species were measured but, because of insufficient numbers, are not included in the statistical analyses; however, they are included in the deciduous analyses. They are mockernut hickory (*Carya tomentosa*), American elm (*Ulmus americana*), pecan (*Carya illinoensis*), and white ash (*Fraxinus americana*). A number of other fairly common species were found at the collection sites but were not measured. These included American holly (*Ilex opaca*), American hornbeam (*Carpinus caroliniana*), sycamore (*Plantanus occidentalis*), flowering dogwood (*Cornus florida*), and river birch (*Betula nigra*).

4. **Field Data Collection Sites**. The field data collection sites were located in northern and north-central Virginia on the eastern fringes of the Piedmont. The topography of the areas generally consists of flat fields to gently rolling slopes. Local relief is generally less than 100 feet. In a number of data collect areas, the landscape was more dissected as streams cut through forested areas. Soils of the region are generally Ultisols and Vertisols.

Figure 1 shows the relative locations of the collection sites at which the tree specimens were measured. The numbers in Figure 1 correspond to the following numbered paragraphs that describe the collection sites in detail.

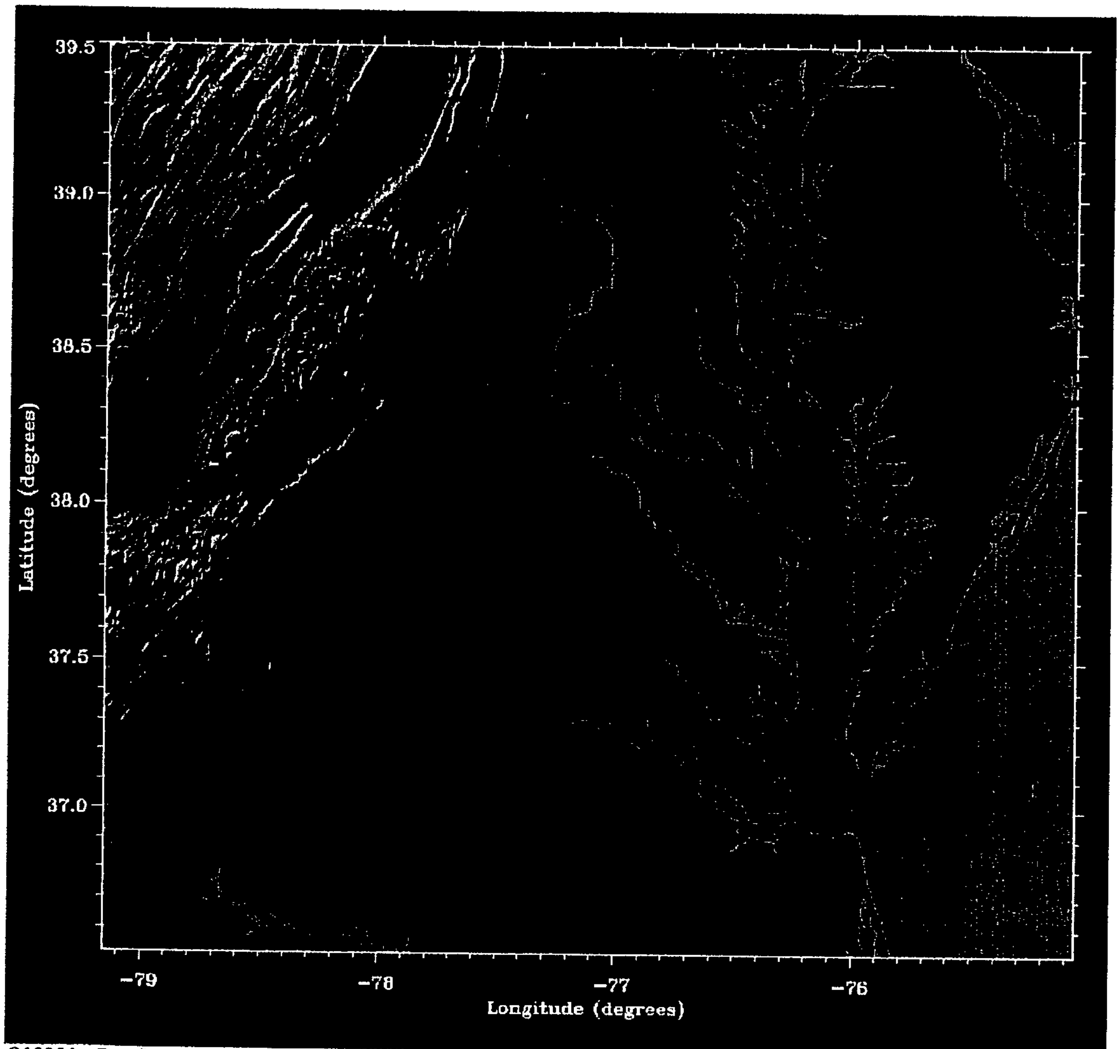

Figure 1. Data Collection Sites

1. **Fort A.P. Hill, Bowling Green, VA.** Fort A.P. Hill is a U.S. Army training installation located approximately 15-20 miles south of Fredericksburg, VA. The topography is generally flat, with numerous bottomlands and marshy areas. There also are locations on the Fort that present a more dissected landscape where creeks cut through forested areas. A total of nine separate data collections were conducted on this facility and 253 specimens were measured. The most abundant naturally occurring species include *Q. alba*, *Q. velutina*, *Q. falcata*, *L. tulipifera*, *L. styraciflua*, and *P. virginiana*. *F. grandifolia* is a common understory species that is occasionally found in fairly pure stands. The Loblolly pine (*P. taeda*) is an abundant, introduced species, having been planted many decades before as part of various reforestation programs. Other coniferous species are found at A.P. Hill and form the numerous pine plantations that are commercially harvested.

2. **U.S. Army Topographic Engineering Center (TEC), Alexandria, VA.** TEC is situated approximately 20 miles SSW., of Washington, D.C. in southern Fairfax County. The topography surrounding TEC is generally flat with numerous marshy and swampy areas, many of them seasonal in nature. Four data collects were conducted at this site and 57 individual trees were measured. Trees surrounding TEC comprise both natural, forest-grown stems and those that were planted as landscaping around buildings and parking lots. Primary species include *L. tulipifera*, *L. styraciflua*, *Q. phellos*, and *P. taeda*.

3. **Mary Washington College (MWC), Fredericksburg, VA.** MWC is located approximately one-half mile west of downtown Fredericksburg, VA. The topography of MWC is generally rolling. A single data collect was performed at this site. A total of 34 specimens were measured. The College has been careful over the years to protect forested sites on campus, maintaining them naturally as much as possible. In addition, during the past century, the Horticulture and Biology Departments at MWC have expended resources in planting both indigenous and exotic species – most of these in open, park-like settings. The primary naturally occurring species *are L. tulipifera*, *Q. falcata*, and *A. rubrum*. The most abundant planted species are *Q. phellos* and *P. taeda*.

4. **Residential Subdivision, Spotsylvania County, VA.** This location is a 10-year old residential subdivision located about 5 miles west of Fredericksburg, VA, in northeastern Spotsylvania County. Two data collects were conducted at this site, and 17 specimens were measured. The subdivision was cut out of a young forest of about 30 years in age. Prior to that, the area had been grass-covered fields that supported a horse farm. Larger specimens, especially *Q. alba* and eastern red cedar (*Juniperus virginiana*), also are found at this location. Their primary function appears to have been boundary markers such as fence lines and also paddocks for animals. There also are younger trees that had been planted by homeowners and the homebuilders. The most abundant naturally occurring species were *L. tulipifera* and *L. styraciflua* – both notable pioneer species. Also in abundance is *A. rubrum*, primarily in lower-lying, seasonally marshy areas.

5. **Caledon Natural Area, King George, VA.** This location is a special area set aside by the State of Virginia and managed by Virginia's Department of Conservation and Recreation. The land, donated by a wealthy family, consists of forested hills and wetlands adjacent to the Potomac River. The forests on the property are described as <u>second-growth</u> stands. Many large specimens of *L. tulipifera*, *F. grandifolia*, *Q. alba*, and *Q. velutina* are located at this site. Two data collects were conducted and 69 trees were measured. Some of the tallest specimens (>150 feet) were found at this location.

6. **Fort Belvoir (Main Post), VA**. Fort Belvoir is located along the Potomac River about 20 miles SSW., of Washington, D.C. The area where the data collect took place was flat and of a general park-like setting. One data collect was conducted here and 31 trees (all *Q. alba*) were measured.

7. **Montpelier, VA**. Montpelier is located approximately 40 miles WSW., of Fredericksburg, VA. It was the estate of former President James Madison. The grounds are managed by a historical foundation. The topography is generally rolling. A total of

69 trees were measured during two data collects. The site is notable for the presence of extremely large specimens, both planted and naturally occurring, especially *L. tulipifera*. A number of individual *L. tulipifera* had d.b.h. values > 6 feet (1.8 m).

8. **Motts Reservoir, VA**. Motts Reservoir is located just south of the Rappahannock River in Spotsylvania County, VA, and is managed by Fredericksburg Parks and Recreation. The topography is rolling with many small streams and creeks cutting gullies through the forests surrounding the reservoir. The primary species found were *F. grandifolia*, *Q. alba*, *Q. velutina*, *Q. coccinea*, and *L. styraciflua*. One data collect was conducted here and 81 trees were measured.

9. **Mount Vernon, VA**. Mount Vernon is located approximately 13 miles south of Washington D.C. along the Potomac River and was the estate of former President George Washington. A total of 12 trees were measured during the data collect. The measured trees were large, open-grown specimens located on the grounds surrounding the main house and were planted during Washington's time. They consisted of *L. tulipifera*, *Q. alba*, white ash (*Fraxinus americana*), and pecan (*Carya illinoensis*). A number of these trees have plaques indicating the dates of planting (late 1700s).

10. **Fredericksburg Battlefield, VA**. This battlefield is located approximately 1 mile from downtown Fredericksburg, VA, and is maintained by the National Park Service. The topography is flat to gently rolling. Pre-Civil War photographs of this site show dominance by agricultural fields and little woody vegetation. A total of 19 trees were measured at this location. The dominant trees at this location were *Q. alba*, *Q. velutina*, *Q. falcata*, and *L. tulipifera*.

11. **Spotsylvania National Military Park, VA**. This site is located about 10 miles southwest of Fredericksburg, VA. The topography is flat to gently rolling. As with the Fredericksburg Battlefield, this area had been agricultural fields during the Civil War. The woody vegetation that existed was cut down during this time for fuel and fortifications. A total of 34 trees were measured at this location in two data collections. The primary species found at this location were *Q. alba*, *Q. velutina*, *L. styraciflua*, *L. tulipifera*, and scattered *F. grandifolia*.

IV. RESULTS

1) **Statistics, Curve Fitting, and Discussion**. During collection of the species, the field collect team made an effort to ensure that the d.b.h. values were normally distributed. The d.b.h. measure for each species and group was evaluated using Shapiro-Wilk's 'W' statistic (Statsoft, Inc., 1999). All met the normality criteria. The relationship between average crown diameter and d.b.h. was then examined with a regression analysis and curve-fitting program (Statsoft, Inc., 1999, SPSS, 1997), and the best fit for all tree species was ordinary least-squares linear regression. This corroborates the findings outlined by Dawkins (1964), Sprinz and Burkhart (1987), Lamson (1987), Bonnor (1964), Smith and Gibbs (1970), and others. Multiple regression also was performed to determine what effect the addition of tree height would have on the crown diameter-d.b.h. relationship. In all instances, the coefficient for the height variable was statistically non-significant, adding practically nothing to the relationship. The authors also examined the approach of Cairns (1950) and used a two-term polynomial to estimate d.b.h. from average crown diameter. In all cases, the 2nd-term of the polynomial expression (i.e., βx^2) proved to be statistically non-significant at the 0.05 level.

Table 1 contains basic statistics for the analyzed species. Table 2 presents the linear regression information for the crown-d.b.h. relationship. It readily can be seen from these results that crown diameter is a good predictor of d.b.h. The r^2 values are

Table 1. Statistics for d.b.h.*, Height, and Average Crown Diameter

Species	Variable	n	Mean	Median	Minimum	Maximum	Std. Dev.
White Oak Group	d.b.h. (in)	142	23.6	22.3	3.4	53.8	11.8
	Height (ft)		86.0	85.0	25.0	135	21.4
	Crown Diameter (ft)		45.2	42.0	10.0	104	21.5
Black Oak Group	d.b.h. (in)	151	26.0	24.0	2.7	57.0	12.7
	Height (ft)		93.3	95.0	24.0	160.0	28.3
	Crown Diameter (ft)		50.2	49.0	9.0	94.0	21.4
Yellow-poplar	d.b.h. (in)	131	28.6	27.2	2.0	57.4	14.7
	Height (ft)		107.8	115.5	20.0	175.0	33.3
	Crown Diameter (ft)		46.3	45.5	6.0	94.0	23.0
Sweetgum	d.b.h. (in)	59	16.3	15.1	1.0	33.4	7.5
	Height (ft)		81.0	85.0	11.0	140.0	28.2
	Crown Diameter (ft)		28.3	26.0	6.0	63.0	13.1
Beech	d.b.h. (in)	102	20.6	20.1	1.7	40.1	8.4
	Height (ft)		98.0	104.5	14.0	160.0	27.4
	Crown Diameter (ft)		50.1	50.0	9.0	95	15.6
Loblolly	d.b.h. (in)	52	17.6	17.4	4.2	31.1	5.8
	Height (ft)		65.6	64.0	25.0	115.0	20.9
	Crown Diameter (ft)		29.0	30.0	6.0	58.0	10.5

* Only specimens with d.b.h. values < 60.0 in are considered in this table.

high, indicating that a very high proportion of the variability in d.b.h. can be explained by crown diameter. There are, of course, other variables that impact this structural relationship and can help explain the remaining variability. Some of the more important ones are soil type, soil moisture, local topography, microclimate, site quality, and the history of the individual tree with regard to competition, stress, and disease.

Linear regression takes the form

$$y = \alpha + \beta x + \varepsilon$$

where y is the estimated d.b.h.; α, the y-intercept of the regression line; β, the regression coefficient; **x,** the input average crown diameter; and ε, the error term (i.e., the residuals from regression). Other table information includes: **n**, the number of specimens; the Standard Error **(SE)** of the Estimate (the estimated standard deviation of the residuals around the regression line); **r**, the **correlation coefficient** that indicates the degree of relatedness between the x and y variables (crown and d.b.h. in this case); and $\mathbf{r^2}$, the **coefficient of determination** that measures the proportion of variability in y (d.b.h.), which is explained by x (average crown diameter).

Table 2. Regression Summary for Tree Species

SPECIES	n	α	β*	SE	r	r^2
White Oak Group (3 species)	142	0.326	0.526	4.14	0.938	0.879
Black Oak Group (6 species)	151	-1.650	0.552	4.58	0.932	0.869
Yellow-poplar	131	0.461	0.607	4.58	0.951	0.904
Sweetgum	59	0.882	0.540	2.57	0.944	0.892
Beech	102	-3.715	0.486	3.75	0.897	0.804
Loblolly Pine	52	4.19	0.465	3.20	0.841	0.700
All Deciduous	637	-0.288	0.542	5.65	0.903	0.815

* the computed β coefficients all had P-values that were <0.00001. Small P-values, below a level such as 0.05, indicate statistically significant, nonzero coefficients.

SE provides an indication of the range of predicted y values (d.b.h.) that would be expected to occur. It would be expected that 95 percent of all estimates are within ±2 SE units. As an example from the table, 95 percent of all estimated d.b.h. values of sweetgum are likely to fall within ±5.1 inches of their actual values.

2) **Graphs**. This section contains graphs of the relationships of crown and d.b.h., height and d.b.h., and crown and height. In addition, the residuals from the crown-d.b.h. relationships also are plotted. Whereas the best-fit relationship between crown and d.b.h.

was determined to be linear, the other structural relationships required different equations.

The height-d.b.h. best-fit equation for all investigated tree species was exponential and takes the form

$$y = \alpha * \exp(\beta x) + \varepsilon$$

where: **y** is the predicted d.b.h.; α is the y-intercept, β is the regression coefficient, **x** is the independent variable (height), and ε is the error term. The '**exp**' notation causes **e**, the base of the natural logarithms (2.7183...), to be raised to the power of x (in this case, the term β**x**).

The crown-height best fit equation for all investigated tree species was logarithmic and takes the form

$$y = \alpha + \beta(\log_{10}(x)) + \varepsilon$$

where **y** is the predicted d.b.h., α is the y-intercept, β is the regression coefficient, **x** is the independent variable (crown), and ε is the error term. The '$\log_{10}$' notation denotes the common logarithm of a positive **x** to the base 10.

Figures 2 through 7 comprise the graphs for each species (or group). Each species (or group) has four associated graphs, Graphs A to D. Graph A contains the linear regression of average crown diameter vs. d.b.h. As a general rule, the majority of open-grown trees fell above the regression lines and forest-grown specimens fell below. As discussed earlier in this report, however, there were a large number of specimens that had been open-grown in the past and now reside within a forest setting and vice versa; hence, it was virtually impossible to add additional regression lines – one for open-grown trees and one for forest-grown trees. Graph B displays the residuals from the linear regression in Graph A. The structure exhibited by the residuals shows a fairly good random pattern. Graph C shows the regression of tree height vs. d.b.h. and Graph D presents the regression for crown diameter vs. tree height. The data for Graphs C and D were not statistically analyzed in depth. The graphs are presented to merely indicate the overall relationships that were uncovered.

The primary regression lines of all the species are shown in Figure 8. The slopes of the lines are similar. Five of the six regression lines overlap at some point. The

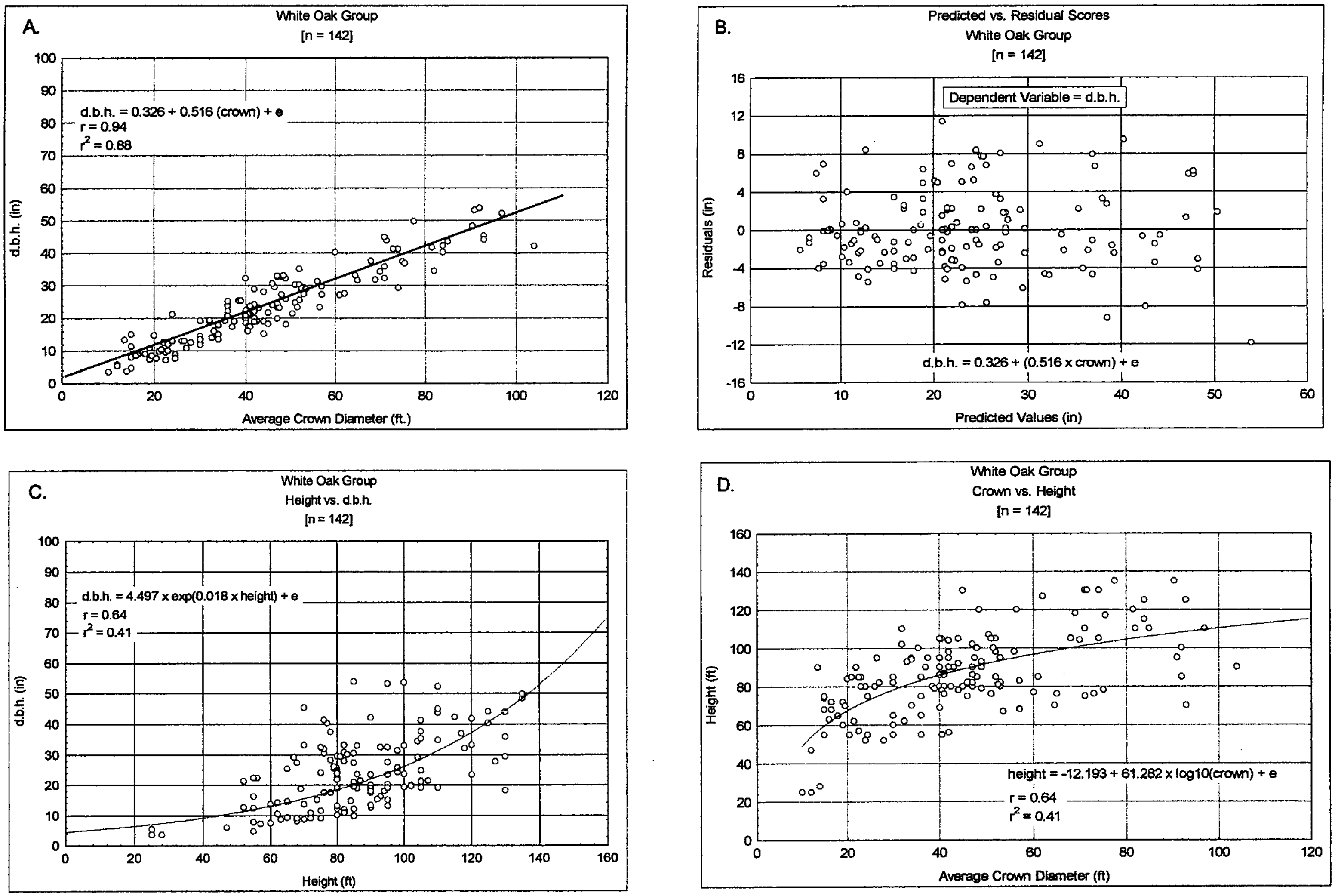

Figure 2. White Oak Group

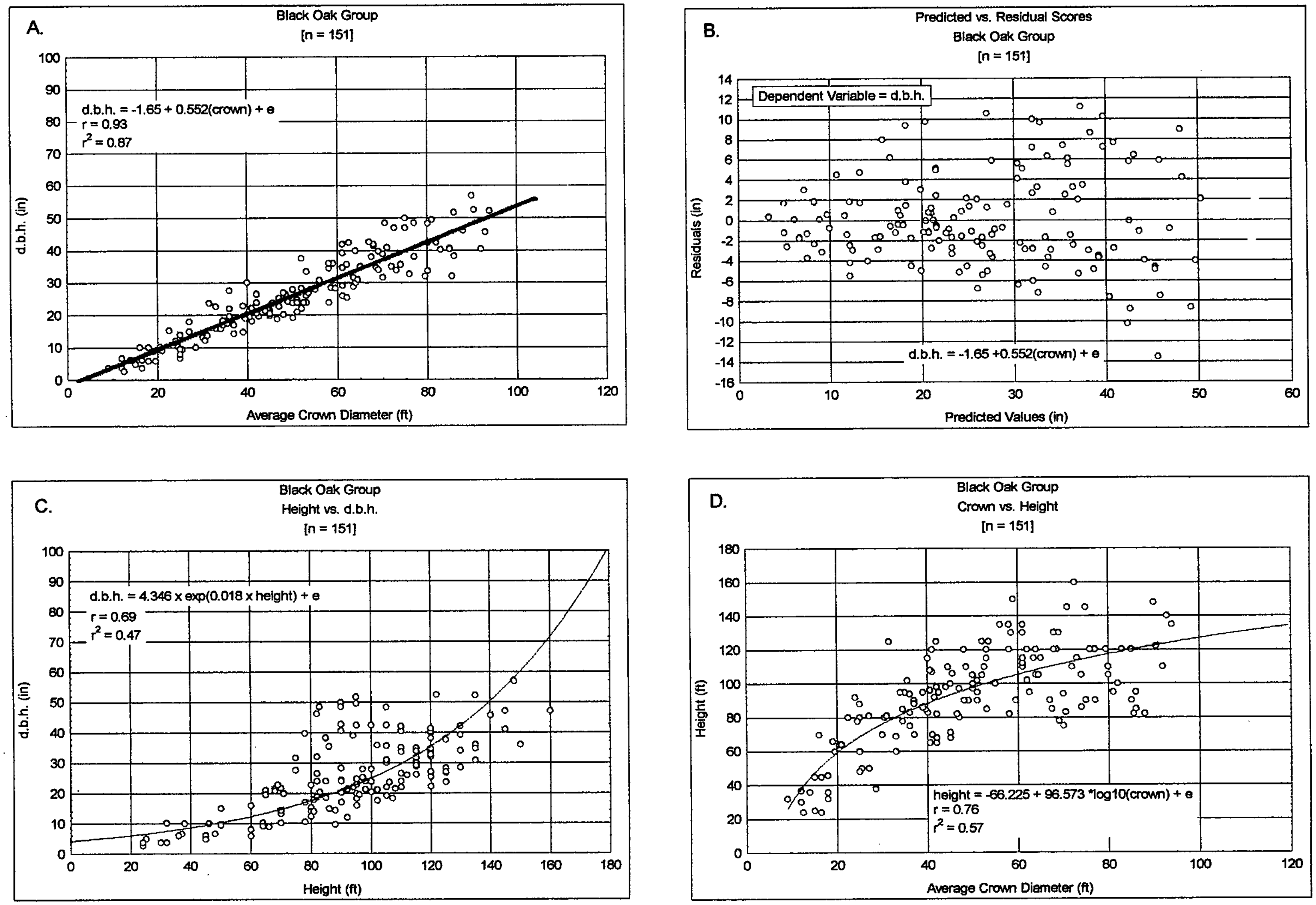

Figure 3. Black Oak Group

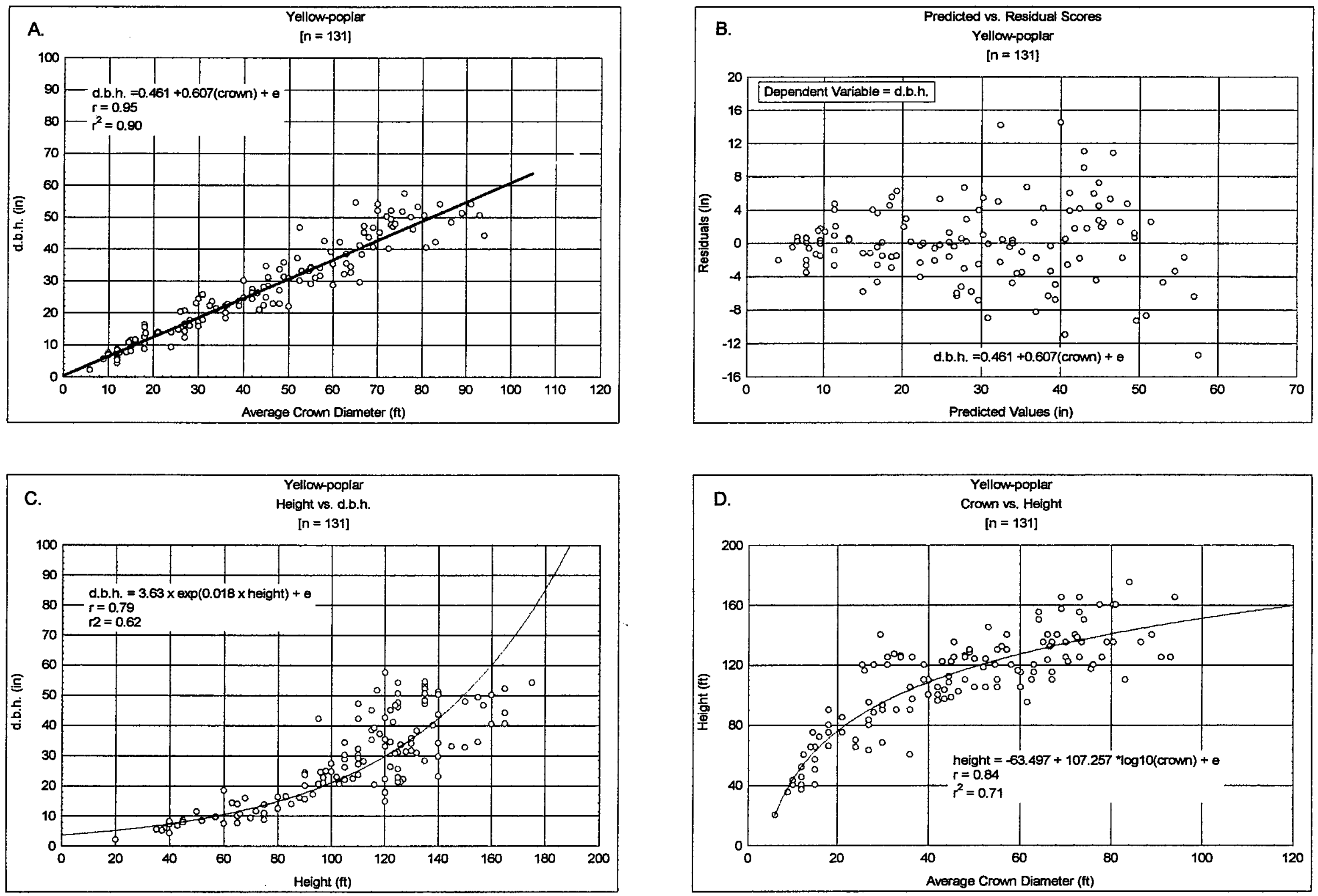

Figure 4. Yellow-poplar

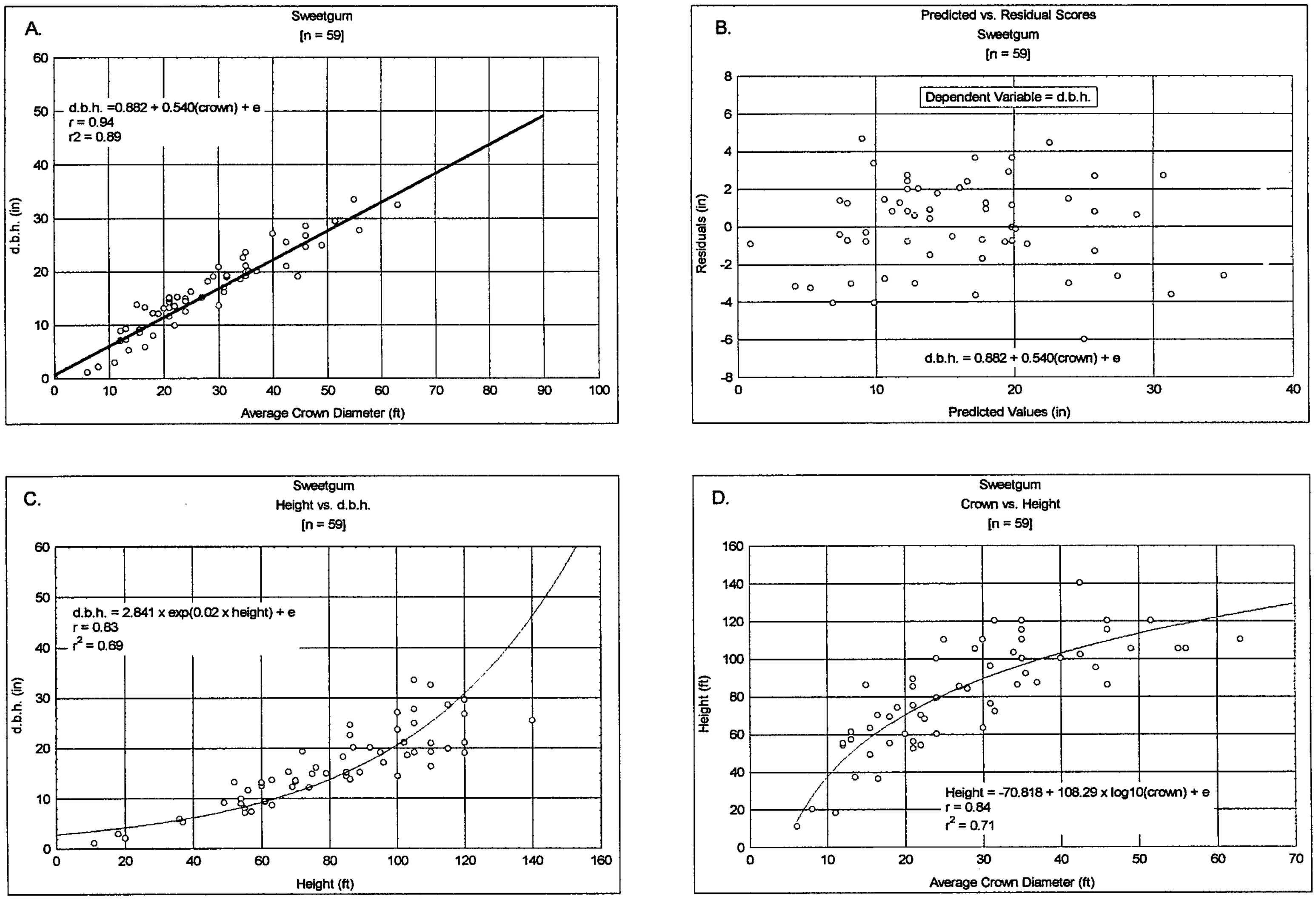

Figure 5. Sweetgum

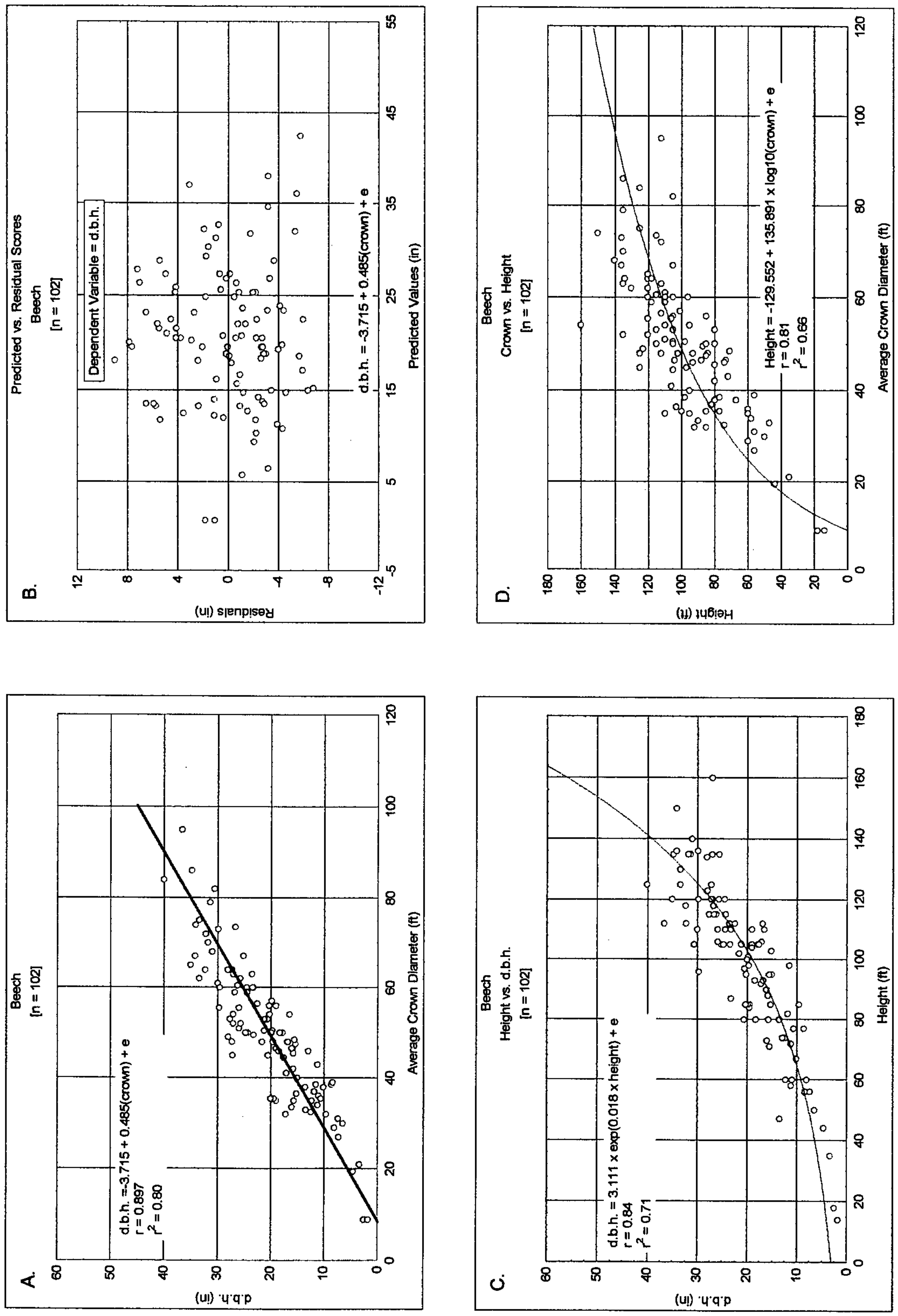

Figure 6. Beech

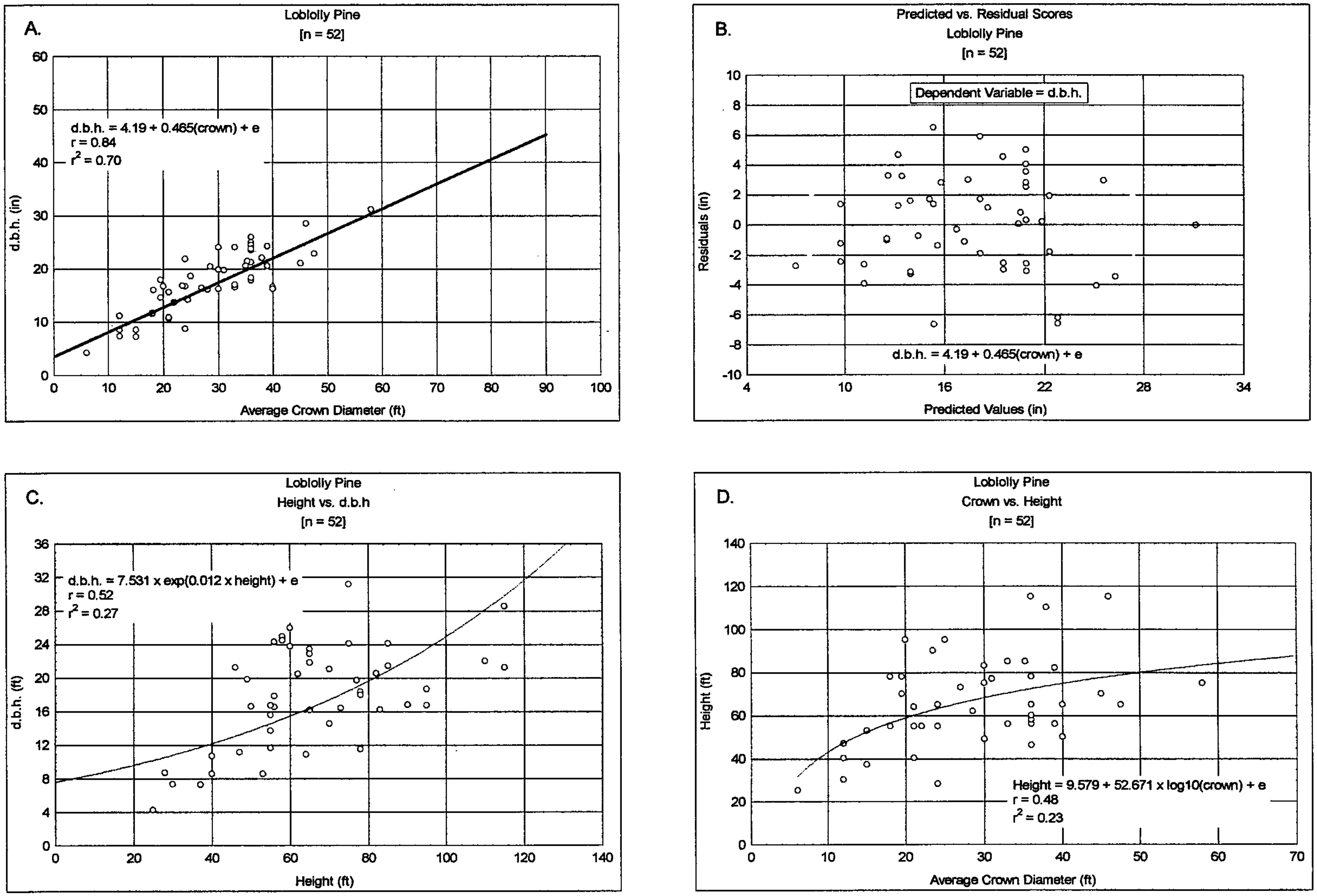

Figure 7. Loblolly Pine

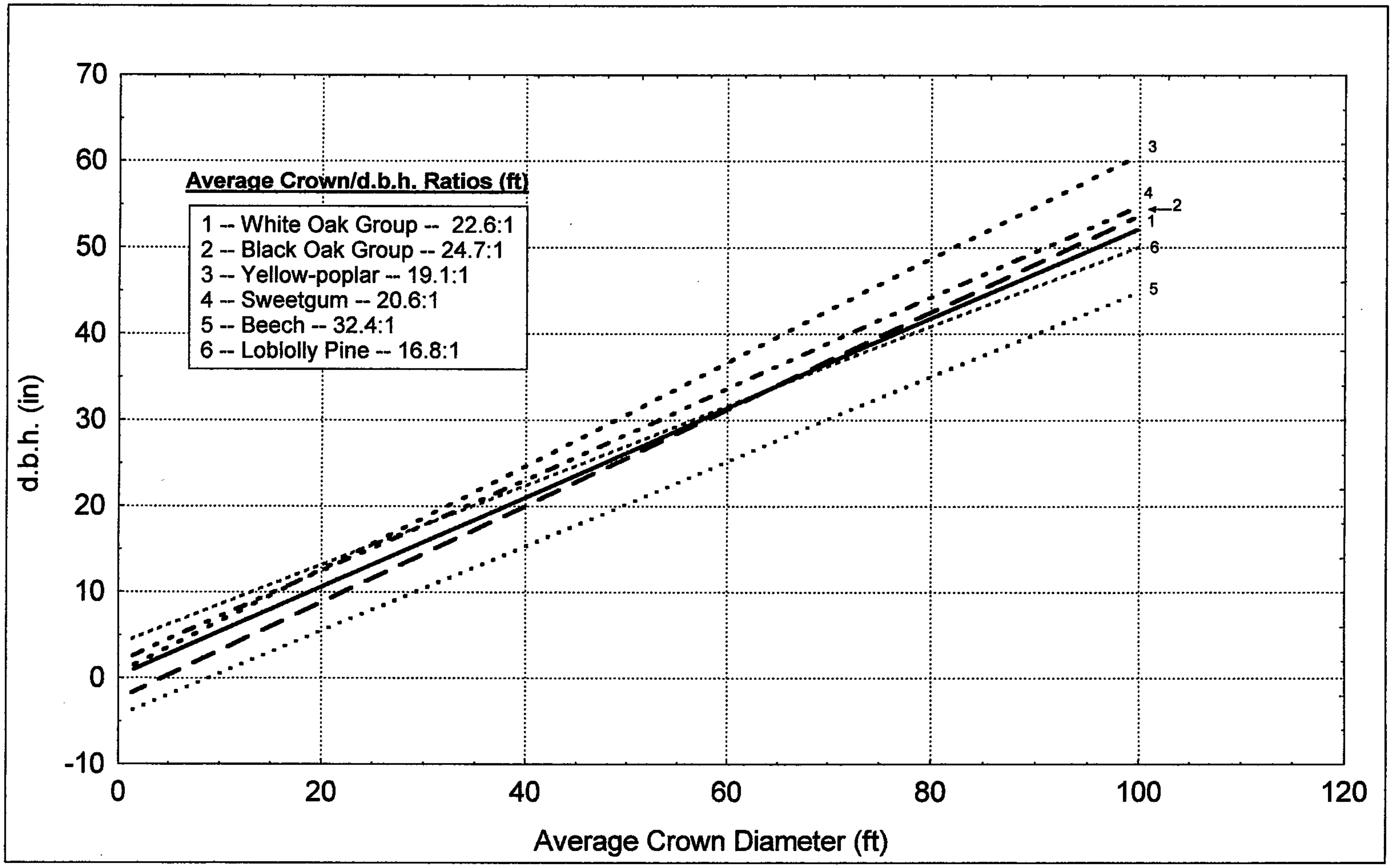

Figure 8. Regressions and Crown/d.b.h. Ratios for Analyzed Species and Groups

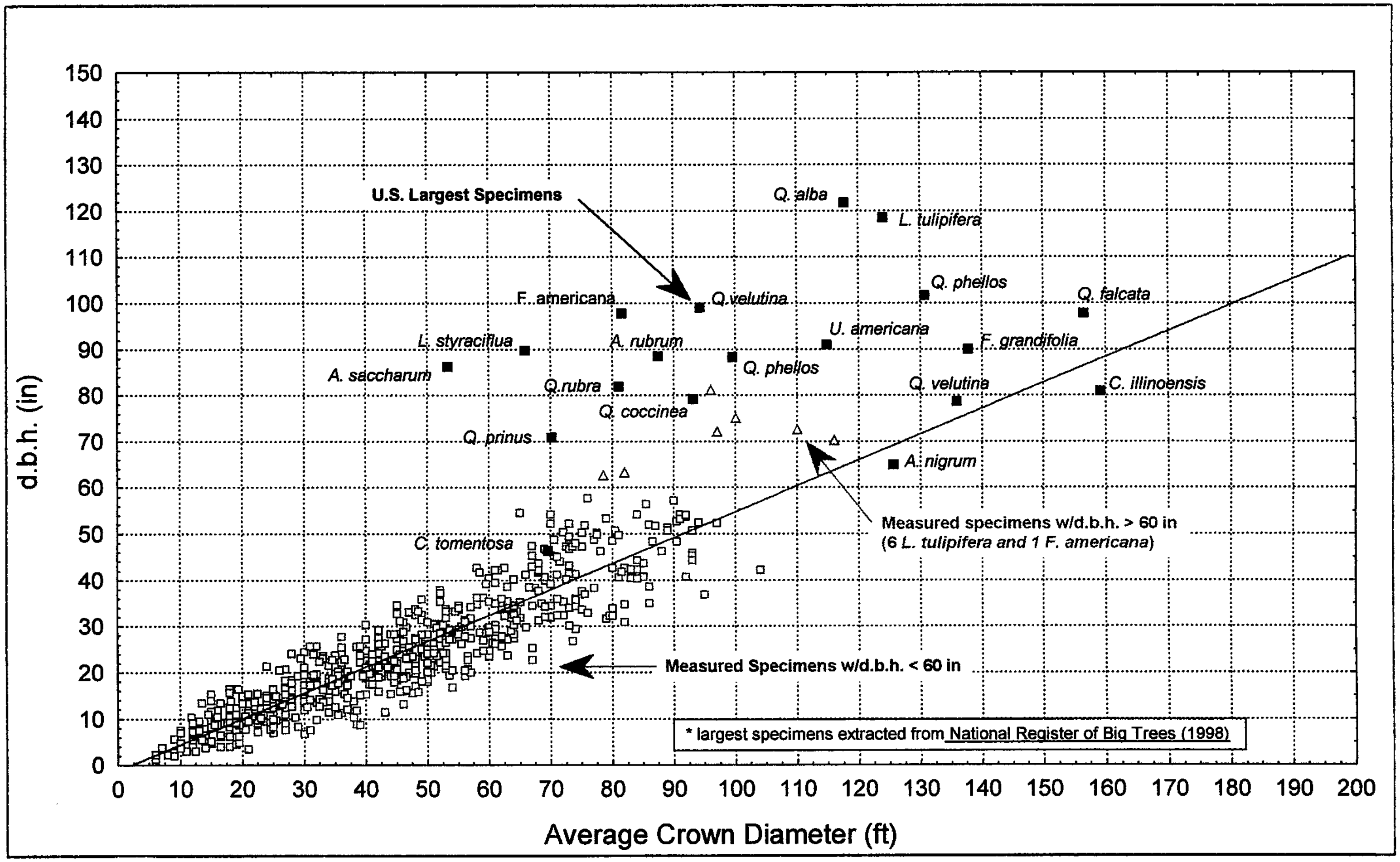

Figure 9. All Measured Deciduous Specimens and U.S. Largest Specimens*

F. americana (Beech) regression line (Number 5) is separate from the other lines. *F. americana* is primarily an understory species and is extremely shade tolerant. The inset on Figure 8 shows the average crown diameter-d.b.h. relationships expressed in feet. Highly shade-intolerant species, such as *L. tulipifera* and *L. styraciflua*, exhibit small ratios, whereas a highly shade-tolerant species, *F. americana*, shows a much larger ratio.

A crown diameter-d.b.h. plot of all deciduous species is shown in Figure 9. The seven specimens with d.b.h. values > 60.0 in. are included, as are the largest specimens for the field measured species found in the National Registry of Big Trees (American Forests, 1998). It can be seen that the measured deciduous specimens with d.b.h. values < 60 in. generally maintain the linear relationship throughout this d.b.h. span. Above 60 in. d.b.h., several species maintain this linear structure. Most species, however, begin exhibiting a growth pattern that may indicate a finite structural limit to the crown dimension with an almost exponential growth in the d.b.h.

V. CONCLUSIONS

1) A simple linear regression best describes the relationship between average crown diameter and d.b.h. This proved true for all analyzed species and is in agreement with the findings of prior research conducted in both mid-latitude temperate and tropical forests across a variety of tree species. This basic finding is important to the application of crown diameter/d.b.h. relationships in quantitative remote sensing. The regression equations provide reliable estimates of individual stem diameters given the width of the tree crown as determined from remotely sensed imagery.

2) The developed linear regressions provide fairly good estimators of d.b.h. from crown diameter measurements in both even-aged forests, and balanced, uneven-aged stands. Sampling was very limited within even-aged forests across all of the sample locations. The majority of the measured stems were hardwoods that had matured within uneven-aged canopies. The overstories in these stands supported balanced age classes and generally were greater than 70 percent crown closure.

3) All species showed rather distinct upper and lower bounds (i.e., tight clusters) in their crown diameter-d.b.h. distributions indicating an adherence to within-species phenotypic structural relationships.

4) The crown diameter-d.b.h. relationship is uniform throughout the full range of d.b.h. values up to approximately 60 in. Beyond this size class, the relationship is typically not linear.

5) The crown diameter-d.b.h. relationships appear unaffected to any great degree in terms of open- or forest-grown individual life histories. Typically, stem height, d.b.h., and crown width are controlled by the density of the stand in which the individual matures; however, the relationships, or ratios, between these variables remain constant across varying stand densities.

6) Crown diameter-d.b.h. relationships appear to be fairly constant across varying site indices. As with stand density, this research confirms that while individuals attain overall larger sizes on high quality sites, the within-stem structural relationships do not vary greatly among sites.

7) The slopes of the linear regression lines for all the dominant and co-dominant deciduous species exhibit a high degree of congruency.

VI. RECOMMENDATIONS

1) The developed regression models should be field tested near the same collection sites. High resolution airborne multispectral imagery will be acquired over one specific site to provide crown diameter measures. The predicted stem diameters will be compared to d.b.h. measures collected from field sampling.

2) Accuracy of crown measurement, vis-à-vis field data collection and photo interpretation, should be explored further.

3) Testing should be performed on the same species in other geographic regions.

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